

Identifying the underlying physics of the ridge via 3-particle $\Delta\eta - \Delta\eta$ correlations

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Abstract

We present the first results on 3-particle $\Delta\eta$ - $\Delta\eta$ correlations in minimum bias d +Au, peripheral and central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured by the STAR experiment. The analysis technique is described in detail. The ridge particles, observed at large $\Delta\eta$ in dihadron correlations in central Au+Au collisions, appear to be uniformly distributed over the measured $\Delta\eta$ - $\Delta\eta$ region in 3-particle correlation. The results, together with theoretical models, should help further our understanding of the underlying physics of the ridge.

1 Introduction

Dihadron correlations provide a powerful tool to study the properties of the medium created in ultra-relativistic heavy-ion collisions. The observation of the near-side ridge in central Au+Au collisions [1, 2], where hadrons are correlated with a high transverse momentum (p_{\perp}) trigger particle in the azimuthal angle ($\Delta\phi \sim 0$) but distributed approximately uniformly in pseudorapidity ($\Delta\eta$), has generated great interest. The properties of ridge particles, such as their p_{\perp} spectral shape and particle compositions, are similar to those of inclusive particles, however the origin of the ridge is presently not understood. Various theoretical models have been proposed, including longitudinal flow push [3], QCD bremsstrahlung radiation boosted by transverse flow [4, 5], recombination between thermal and shower partons at intermediate p_{\perp} [6], broadening of quenched jets in turbulent color fields [7], and elastic collision between hard and medium partons (momentum kick) [8]. Production of correlated particles in all these models can be broadly divided into two categories: (1) particles from jet fragmentation in vacuum which generate a jet-cone peak in dihadron correlation, and (2) particles from gluon radiation affected by the medium and diffused broadly in $\Delta\eta$ which generate the ridge. However, the qualitative features of dihadron correlations are all same from these models. On the

other hand, because the physics mechanisms of gluon diffusion in $\Delta\eta$ differs between models, the distribution of two ridge particles in coincidence with the trigger particle can differ. Therefore, we analyze the 3-particle correlation in $\Delta\eta$ - $\Delta\eta$ between two associated particles and a trigger particle to potentially discriminate between the physics mechanisms proposed in these models. Jet fragmentation in vacuum would give a peak around $(\Delta\eta_1, \Delta\eta_2) \sim (0, 0)$ in 3-particle $\Delta\eta$ - $\Delta\eta$ correlations. Particles from $\Delta\eta$ diffusion would produce structures that depend on the physics mechanisms of diffusion and thus can be used to discriminate models. Combinations of one particle from jet fragmentation in vacuum and the other from $\Delta\eta$ gluon diffusion would generate horizontal or vertical strips in 3-particle $\Delta\eta$ - $\Delta\eta$ correlations.

2 Analysis technique and systematic uncertainties

The data used in this analysis are from d +Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and were taken by the STAR Time Projection Chamber (TPC) [9]. The Au+Au collisions were recorded with the minimum bias trigger and central trigger from zero degree calorimeters. The z -position of the constructed primary vertex (collision point) was restricted within ± 30 cm from the center of the TPC. To ensure that these tracks come from the collision, the distance of closest approach to the primary vertex of less than 3.0 cm was used. The number of track points in the TPC was required to be greater than 15. The trigger and associated particles are restricted to $|\eta| < 1$ and their p_\perp ranges are $3 < p_\perp^{trig} < 10$ GeV/c and $1 < p_\perp^{assoc} < 3$ GeV/c, respectively. The correlation yields are corrected for the centrality-, p_\perp -, ϕ -dependent reconstruction efficiency for associated particles and the ϕ -dependent efficiency for trigger particles, and are normalized per corrected trigger particle.

Figure 1 (a) shows the 2-particle correlation signal in $\Delta\phi$ for 0-12% central Au+Au collisions, $Y(\Delta\phi)$. Also shown is the background constructed from the event-mixing technique, mixing a trigger particle from a triggered event with an associated particle from another event from the inclusive data sample. The inclusive event is required to have the same centrality, same magnetic field configuration and similar primary vertex z position ($|\Delta z| < 1$ cm) as for the triggered event. The flow contribution is added by hand for the associated particle as it is not preserved in the mixed event background $B_{inc}(\Delta\eta, \Delta\phi)$. The mixed event background is then scaled by a constant a :

$$B(\Delta\phi) = a \int_{-1}^1 B_{inc}(\Delta\eta, \Delta\phi) \left[1 + 2v_2^{trig} v_2^{assoc} \cos(2\Delta\phi) + 2v_4^{trig} v_4^{assoc} \cos(4\Delta\phi) \right] d(\Delta\eta). \quad (1)$$

This normalization was performed in the $0.8 < \Delta\phi < 1.2$ range to match the correlation signal assuming zero yield at $\Delta\phi = 1$ radian (ZYA1). The v_2 and v_4 are the anisotropic flow coefficients, and are measured to be independent of η [10].

Figure 1 (b) shows the $\Delta\eta$ distribution within $|\Delta\phi| < 0.7$ on the near side. The background constructed from mixed event is scaled by the same a factor as obtained by

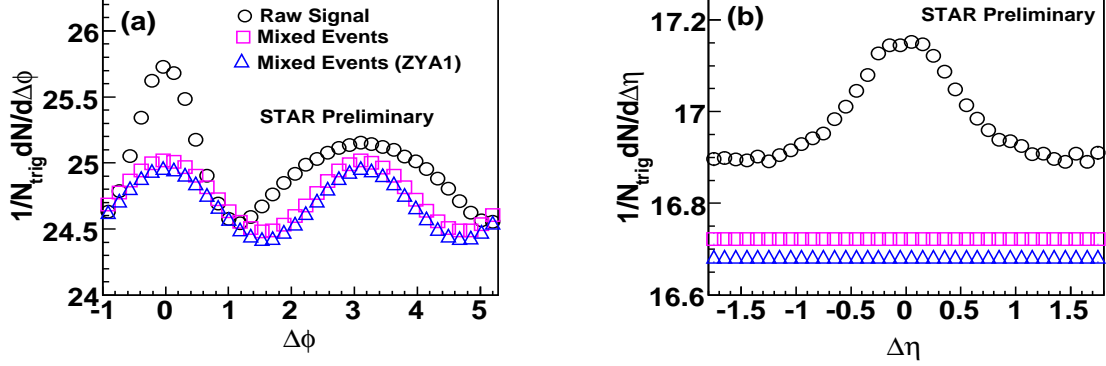


Figure 1: Two-particle $\Delta\phi$ and $\Delta\eta$ correlations in 0-12% central Au+Au collisions are plotted in (a) and (b) respectively. The mixed event background (before and after a scaling) are also shown. Both the trigger and associated particles are restricted to $|\eta| < 1$. The trigger and associated particles p_{\perp} ranges are $3 < p_{\perp}^{\text{trig}} < 10$ GeV/c and $1 < p_{\perp}^{\text{assoc}} < 3$ GeV/c, respectively. The $\Delta\eta$ distributions are obtained for near-side associated particles within $|\Delta\phi| < 0.7$. All $\Delta\eta$ correlations are corrected for the 2-particle $\Delta\eta$ acceptance.

the 2-particle ZYA1 in $\Delta\phi$:

$$B(\Delta\eta) = a \int_{-0.7}^{0.7} B_{\text{inc}}(\Delta\eta, \Delta\phi) \left[1 + 2v_2^{\text{trig}} v_2^{\text{assoc}} \cos(2\Delta\phi) + 2v_4^{\text{trig}} v_4^{\text{assoc}} \cos(4\Delta\phi) \right] d(\Delta\phi). \quad (2)$$

The correlated 2-particle yield is given by:

$$\hat{Y}(\Delta\eta) = Y(\Delta\eta) - B(\Delta\eta). \quad (3)$$

In Figure 1 (b), the additional 2-particle $\Delta\eta$ acceptance, $A(\Delta\eta)$, is applied on both the signal, $Y(\Delta\eta)/A(\Delta\eta)$, and the background, $B(\Delta\eta)/A(\Delta\eta)$. The broad jet-like peak around $\Delta\eta \sim 0$ is observed, and this peak sits atop of a relatively flat structure which represents the ridge.

The 3-particle correlation raw signal, $Y(\Delta\eta_1) \otimes Y(\Delta\eta_2)$, is obtained from all triplets of one trigger particle and two associated particles from the same triggered event. The associated particles were constrained in azimuthal angle relative to the trigger particle within $|\Delta\phi| < 0.7$. The signal is binned in $\Delta\eta_1$ and $\Delta\eta_2$, the pseudorapidity differences between the associated particles and the trigger. The raw 3-particle correlation signal can be formulated as:

$$Y(\Delta\eta_1) \otimes Y(\Delta\eta_2) = \hat{Y}(\Delta\eta_1) \otimes \hat{Y}(\Delta\eta_2) + B(\Delta\eta_1) \otimes B(\Delta\eta_2) + \left[\hat{Y}(\Delta\eta_1) \otimes B(\Delta\eta_2) + \hat{Y}(\Delta\eta_2) \otimes B(\Delta\eta_1) \right] \quad (4)$$

where $\hat{Y}(\Delta\eta)$ and $B(\Delta\eta)$ represent the correlated and background particles, respectively. The two sources of background in the raw 3-particle correlation are: (1) one of the two

associated particles is correlated with the trigger particle besides flow correlation, and (2) neither of the two associated particles is correlated with the trigger particle besides flow correlation.

The first background, referred to as Hard-Soft (HS), cannot be readily obtained from the folding of the background subtracted 2-particle correlation with the underlying background because of the non-uniform $2\text{-particle } \Delta\eta$ acceptance. The folding would result in the product of two averages, the average 2-particle correlation, $\hat{Y}(\Delta\eta)$, and the average background, $B(\Delta\eta)$. Since $\hat{Y}(\Delta\eta)$ and $B(\Delta\eta)$ are correlated event-by-event because of the $\Delta\eta$ acceptance, the average of the product does not equal to the product of the averages. Instead we construct the HS by mixing trigger-associated pair from the triggered event with a particle from a different and inclusive event. Namely,

$$\begin{aligned} HS &= \hat{Y}(\Delta\eta_1) \otimes B(\Delta\eta_2) + \hat{Y}(\Delta\eta_2) \otimes B(\Delta\eta_1) \\ &= a \left[Y(\Delta\eta_1) B_{\text{inc}}(\Delta\eta_2) \right] F^{(2)} + a \left[Y(\Delta\eta_2) B_{\text{inc}}(\Delta\eta_1) \right] F^{(1)} \\ &\quad - 2a^2 \left[B_{\text{inc}}(\Delta\eta_1) B_{\text{inc}}(\Delta\eta_2) \right] F. \end{aligned} \quad (5)$$

Here the last term is constructed by mixing two different inclusive events to take care of the uncorrelated part in the first two terms of the Eq. 5. The $F^{(1)}$ and $F^{(2)}$ are to take into account the flow correlation related to associated particle 1 and 2, respectively, and are given by:

$$\begin{aligned} F^{(1)} &= \langle 1 + 2v_2^{\text{trig}} v_2^{(1)} \cos(2\Delta\phi_1) + 2v_2^{(1)} v_2^{(2)} \cos(2\Delta\phi_1 - 2\Delta\phi_2) + 2v_4^{\text{trig}} v_4^{(1)} \cos(4\Delta\phi_1) \\ &\quad + 2v_4^{(1)} v_4^{(2)} \cos(4\Delta\phi_1 - 4\Delta\phi_2) + 2v_2^{\text{trig}} v_2^{(1)} v_4^{(2)} \cos(2\Delta\phi_1 - 4\Delta\phi_2) \\ &\quad + 2v_2^{\text{trig}} v_2^{(2)} v_4^{(1)} \cos(4\Delta\phi_1 - 2\Delta\phi_2) + 2v_2^{(1)} v_2^{(2)} v_4^{\text{trig}} \cos(2\Delta\phi_1 + 2\Delta\phi_2) \rangle \end{aligned} \quad (6)$$

and an analogous equation for $F^{(2)}$ with $1 \leftrightarrow 2$. The F is to take into account the flow correlation among all the three particles in the event mixing, and is given by

$$\begin{aligned} F &= \langle 1 + 2v_2^{\text{trig}} v_2^{(1)} \cos(2\Delta\phi_1) + 2v_2^{\text{trig}} v_2^{(2)} \cos(2\Delta\phi_2) + 2v_2^{(1)} v_2^{(2)} \cos(2\Delta\phi_1 - 2\Delta\phi_2) \\ &\quad + 2v_4^{\text{trig}} v_4^{(1)} \cos(4\Delta\phi_1) + 2v_4^{\text{trig}} v_4^{(2)} \cos(4\Delta\phi_2) + 2v_4^{(1)} v_4^{(2)} \cos(4\Delta\phi_1 - 4\Delta\phi_2) \\ &\quad + 2v_2^{\text{trig}} v_2^{(1)} v_4^{(2)} \cos(2\Delta\phi_1 - 4\Delta\phi_2) + 2v_2^{\text{trig}} v_2^{(2)} v_4^{(1)} \cos(4\Delta\phi_1 - 2\Delta\phi_2) \\ &\quad + 2v_2^{(1)} v_2^{(2)} v_4^{\text{trig}} \cos(2\Delta\phi_1 + 2\Delta\phi_2) \rangle. \end{aligned} \quad (7)$$

The averages in Eq. 6, 7 are taken within $|\Delta\phi_{1,2}| < 0.7$. The superscripts represent the v_2 and v_4 for trigger particle and associated particles. We used a parameterization of $v_4 = 1.15v_2^2$. Again, the flow contributions are constant in the measured η range.

The second background, referred to as Sof-Soft (SS), is constructed by mixing a trigger particle with an associated particle pair from an inclusive event which preserves all correlations between the two associated particles:

$$SS = B(\Delta\eta_1) \otimes B(\Delta\eta_2) = a^2 b \left[B_{\text{inc}}(\Delta\eta_1) \otimes B_{\text{inc}}(\Delta\eta_2) \right] F^{(t)} \quad (8)$$

where a is the same factor as obtained from 2-particle ZYA1 in $\Delta\phi$. The flow contribution between trigger particle and the background particles is not preserved in the event mixing. This contribution, the so-called trigger flow, is added by hand:

$$\begin{aligned} F^{(t)} = & \langle 1 + 2v_2^{\text{trig}}v_2^{(1)} \cos(2\Delta\phi_2) + 2v_2^{\text{trig}}v_2^{(2)} \cos(2\Delta\phi_2) + 2v_4^{\text{trig}}v_4^{(1)} \cos(4\Delta\phi_1) \\ & + 2v_4^{\text{trig}}v_2^{(2)} \cos(4\Delta\phi_2) + 2v_2^{\text{trig}}v_2^{(1)}v_4^{(2)} \cos(2\Delta\phi_1 - 4\Delta\phi_2) \\ & + 2v_2^{\text{trig}}v_2^{(2)}v_4^{(i)} \cos(4\Delta\phi_1 - 2\Delta\phi_2) + 2v_2^{(1)}v_2^{(2)}v_4^{\text{trig}} \cos(2\Delta\phi_1 + 2\Delta\phi_2) \rangle \end{aligned} \quad (9)$$

where the average is taken within $|\Delta\phi_{1,2}| < 0.7$.

The factor a^2b in Eq. 8 scales the number of associated pairs from the inclusive event to that in the background underlying the triggered event:

$$b = \frac{\left[\langle N_{\text{assoc}}(N_{\text{assoc}} - 1) \rangle / \langle N_{\text{assoc}} \rangle^2 \right]_{\text{bkgd}}}{\left[\langle N_{\text{assoc}}(N_{\text{assoc}} - 1) \rangle / \langle N_{\text{assoc}} \rangle^2 \right]_{\text{inc}}} \quad (10)$$

where N_{assoc} denotes the associated particle multiplicity. If the associated particle multiplicity in the inclusive event and in the background underlying the triggered event are both Poissonian or deviate from Poissonian equally, then $b=1$. In our analysis, we obtain b in the following way. We scale the 2-particle $\Delta\eta$ distribution such that the ridge contribution in $1.0 < |\Delta\eta| < 1.8$ is zero, and this gives a new a . We repeat our analysis with this new a , and obtain b by requiring the average 3-particle $\Delta\eta$ - $\Delta\eta$ signal in $1.0 < |\Delta\eta_1, \Delta\eta_2| < 1.8$ to be zero. We use the thus obtained b in our analysis with the default a to obtain the final 3-particle correlation. The assumption in this is:

$$\left[\langle N_{\text{assoc}}(N_{\text{assoc}} - 1) \rangle / \langle N_{\text{assoc}} \rangle^2 \right]_{\text{bkgd}} = \left[\langle N_{\text{assoc}}(N_{\text{assoc}} - 1) \rangle / \langle N_{\text{assoc}} \rangle^2 \right]_{\text{bkgd+ridge}}. \quad (11)$$

The 3-particle $\Delta\eta$ - $\Delta\eta$ correlation, $\hat{Y}(\Delta\eta_1) \otimes \hat{Y}(\Delta\eta_2)$, is obtained by subtracting the HS and SS backgrounds from the raw signal. The obtained correlation is corrected for 3-particle $\Delta\eta$ acceptance. The acceptance is obtained from event-mixing of a trigger particle with associated particles from two different inclusive events, as was done for the last term in Eq. 5, namely

$$A(\Delta\eta_1, \Delta\eta_2) = \frac{B_{\text{inc}}(\Delta\eta_1)B_{\text{inc}}(\Delta\eta_2)}{B_{\text{inc}}(0)B_{\text{inc}}(0)}. \quad (12)$$

The main sources of systematic uncertainty in our 3-particle correlation results are from the normalization factors a , b and the flow measurements. The v_2 used in our analysis is the average v_2 from the modified reaction plane method and the 4-particle cummulant method [1]. We assign a $\pm 10\%$ systematic uncertainty on v_2 . The systematic uncertainty on a is estimated by using the normalization range of $0.9 < \Delta\phi < 1.1$ and $0.7 < \Delta\phi < 1.3$. The systematic uncertainty on b is estimated by using the normalization range in $\Delta\eta$ of $-1.8 < |\Delta\eta| < -1.2$ and $-1.2 < |\Delta\eta| < -0.6$.

3 Results and Discussion

Figure 2 (a), (b) and (c) show the background subtracted 3-particle $\Delta\eta$ - $\Delta\eta$ correlation for d +Au, 40-80% Au+Au and 0-12% Au+Au at $\sqrt{s_{NN}} = 200$ GeV, respectively. The prominent jet structure is observed in d +Au and 40-80% Au+Au collisions around

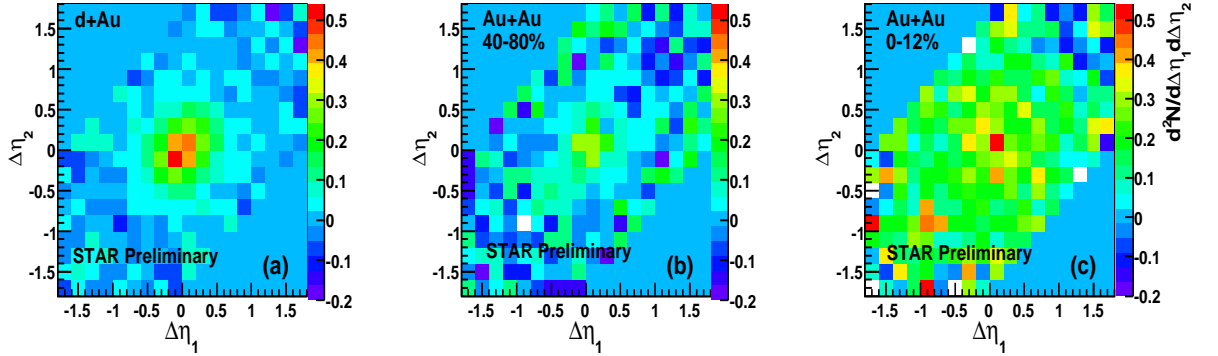


Figure 2: Background subtracted 3-particle $\Delta\eta$ - $\Delta\eta$ correlation in (a) d +Au, (b)40-80% Au+Au and (c) central 0-12% for Au+Au collisions. The trigger and associated particles p_{\perp} ranges are $3 < p_{\perp}^{trig} < 10$ GeV/c and $1 < p_{\perp}^{assoc} < 3$ GeV/c, respectively. The $\Delta\eta$ - $\Delta\eta$ correlations are obtained for near-side associated particles within $|\Delta\phi| < 0.7$. All correlations are corrected for the 3-particle $\Delta\eta$ acceptance.

$(\Delta\eta_1, \Delta\eta_2) \sim (0,0)$. The peak is also observed in 0-12% central Au+Au collisions, but the peak is atop of an overall pedestal. This pedestal is caused by the ridge particles, and does not seem to have other structures in $(\Delta\eta_1, \Delta\eta_2)$. The ridge particles seem to be distributed approximately uniformly over the measured $\Delta\eta$ - $\Delta\eta$ region.

To study the $\Delta\eta$ - $\Delta\eta$ correlation in more detail, Figure 3 (a) and (b) show the projections of the 3-particle $\Delta\eta$ - $\Delta\eta$ correlation along the on-diagonal $\Sigma = (\Delta\eta_1 + \Delta\eta_2)/2$ and off-diagonal $\Delta = (\Delta\eta_1 - \Delta\eta_2)/2$. These projections are performed within $|\Delta| < 0.2$ and $|\Sigma| < 0.2$, respectively. Figure 3 (c) shows the radial $R = \sqrt{(\Delta\eta_1)^2 + (\Delta\eta_2)^2}$ projection. All projections are normalized by the projected area, therefore they are the average correlation signal per radian². The average signals peak at $\Sigma \sim 0$ or $\Delta \sim 0$, in d +Au and 40-80% Au+Au collisions and rapidly fall off to zero at large Σ or Δ . For central 0-12% Au+Au collisions the signal also peaks at $\Sigma \sim 0$ and $\Delta \sim 0$ and is broadly distributed. The radial projection is peaked at $R \sim 0$ and drops gradually with R and perhaps flattens out in central 0-12% Au+Au collisions. Figure 3 (d) shows the angular projection $\xi = \tan^{-1}(\Delta\eta_2/\Delta\eta_1)$ in $0.7 < R < 1.4$. The average signal over ξ shows no evidence for horizontal or vertical strips in the $\Delta\eta$ - $\Delta\eta$ correlation.

Our results suggest that the ridge particles in the central 0-12% Au+Au collisions are uncorrelated in $\Delta\eta$ between themselves. The ridge appears to be uniform event-by-event. We also observe the small $\Delta\eta$ peak, suggesting contributions from jet fragmentation in

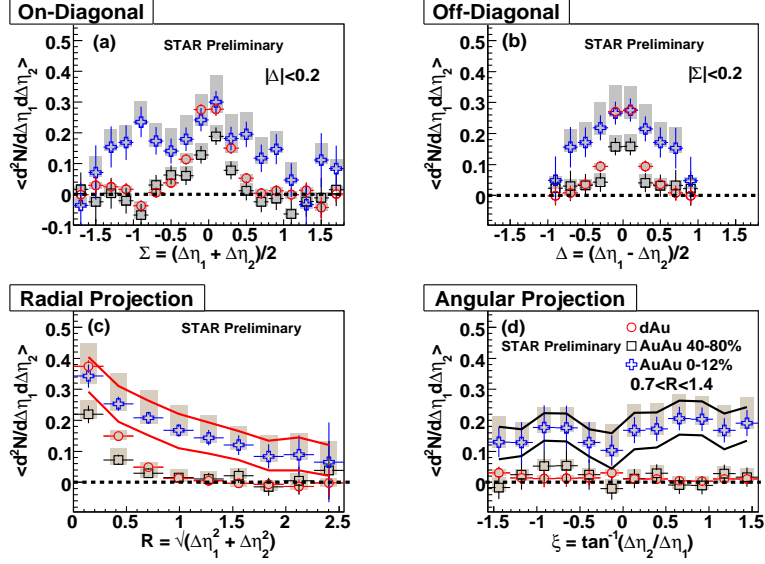


Figure 3: Projections of the background subtracted 3-particle $\Delta\eta$ - $\Delta\eta$ correlations in d +Au, 40-80% Au+Au and 0-12% central Au+Au collisions. Panels (a)-(d) show the on-diagonal, off-diagonal, radial and angular projections, respectively. The shaded box represent the systematic uncertainty due to background normalization and the solid lines represents the systematic uncertainty due to flow subtraction.

vacuum. However, the two contributions, one from jet fragmentation in vacuum, the other from the ridge, do not seem to co-exist in the same event because we do not observe the horizontal and vertical strips in $\Delta\eta$ - $\Delta\eta$ correlation. Since no plausible physics excludes the co-existence of these two effects, our results indicate that the probability of such a co-existence is small.

4 Summary and outlook

We have presented the first results on 3-particle $\Delta\eta$ - $\Delta\eta$ correlation for d +Au, 40-80% Au+Au and 0-12% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. A correlation peak at $(\Delta\eta_1, \Delta\eta_2) \sim (0,0)$ characteristic of jet fragmentation in vacuum, is observed in all systems. This peak sits atop of a pedestal in central 0-12% Au+Au collisions. This pedestal, composed of particle pairs from the ridge, is approximately uniform or broadly falling within the measured $\Delta\eta$ acceptance. No other significant structures, except that from jet fragmentation in vacuum, were observed in the projection. The ridge particles are uncorrelated among themselves in $\Delta\eta$. The ridge is uniform event-by-event.

To understand the physics mechanism(s) generating the ridge, quantitative model calculations are clearly needed. These results in comparison to theoretical models and high statistic data sets will help further our understanding of the underlying physics of

the ridge.

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